INTELLIGENT PROCESSING OF THICK COMPOSITES

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14. ABSTRACT
Composites consolidation in various manufacturing processes has been studied from a unified point of view to develop a simulation model. As a result a master formulation is now available and can be tailored to each manufacturing process. Process simulation codes have been developed for the resin transfer molding (RTM) and autoclave/compression molding processes. The other key results are: (1) development of a finite element code RTMSIM to simulate resin transfer molding process; (2) development of a simple analytical model to explain the mechanisms of enhanced mold filling when high-permeability layers are used; (3) development of a rapid prototyping method for RTM based on the laminated object manufacturing process; (4) development of an intelligent thermal control system to ensure a better temperature uniformity in compression molding; (5) development of a unified process simulation model; and (6) development of a new kinetics model.

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ABSTRACT

Optimizing manufacturing processes through trial and error is an expensive and time-consuming approach. An ideal approach would be to optimize the process off-line and control the resulting process adaptively for any anomalies that might be introduced inadvertently. Such an intelligent manufacturing would ensure high structural integrity and low cost for Navy composite structures. The present research is a first step toward this goal.

Composites consolidation in various manufacturing processes has been studied from a unified point of view to develop a simulation model. As a result a master formulation is now available and can be tailored to each manufacturing process. Process simulation codes have been developed for the resin transfer molding and autoclave/compression molding processes. The other key results are summarized below:

1. A finite element code RTMSIM has been developed to simulate RTM. The code can handle non-isothermal injection of reacting, non-Newtonian resins. It fully employs a finite element formulation without the use of control volumes, and therefore facilitates design and manufacturing integration.

2. A simple analytical model has been developed to explain the mechanisms of enhanced mold filling when high-permeability layers (HPLs) are used. The effective permeability was shown to be almost the same as that of the high-permeability layer alone.

3. A rapid prototyping method based on the laminated object manufacturing process has been developed for RTM molds. The molds made of paper can be used for room-temperature RTM when their surfaces are treated properly.

4. An intelligent thermal control system has been developed to ensure a better temperature uniformity through the thickness of thick composites. The system uses forecasting of future temperature rise in its decision process.

5. A unified process simulation model has been developed to bring analyses of different manufacturing processes under a general framework. The resulting master equation can be simplified depending on the pertinent process conditions.

6. A new cure kinetics model has been developed to eliminate some of the inconsistencies inherent in the existing models. The new model correctly satisfies the condition that a full cure may not be achieved at low temperatures.

1.0 INTRODUCTION

Optimizing manufacturing processes through trial and error is an expensive and time-consuming approach. An ideal approach would be to optimize the process off-line and control the resulting process adaptively for any anomalies that might be introduced inadvertently. Such an intelligent manufacturing would ensure high structural integrity and low cost for Navy composite structures. The present research is a first step toward this goal.

Intelligent manufacturing requires a clear understanding of manufacturing processes involved, the ability to simulate the material and geometric changes during processing, and the techniques to control the processing parameters adaptively to produce the part as designed. These three key ingredients were studied in detail for the following two manufacturing processes: compression molding and resin transfer molding (RTM). The former is a typical manufacturing process for prepregs and the latter for textile composites. For both processes, simulation models were developed and validated through experimental correlation.

2.0 APPROACH

The research consisted of 3 tasks: composites consolidation, resin transfer molding, and intelligent cure control.

2. 1 Task 1: Composites Consolidation

A critical literature survey was conducted to evaluate various process simulation models for thermosetting matrix composites that had been proposed. A unified model was then developed to describe resin flow and fiber compaction regardless of the manufacturing process used.

For thermoplastic matrix composites a simulation model was developed for the tape placement process. The model included heat transfer, viscoelastic stress development, and bonding through autohesion.

2. 2 Task 2. Resin Transfer Molding

The conventional approach to RTM simulation is based on a combination of finite-element and control volume approaches. This finite element/control volume approach places a limit on the types of elements that can be used and hence may pose a compatibility problem with structural design. Therefore, a finite-element approach was used to develop a simulation model for RTM. In addition, the unified model developed in Task 1 was used to modify an existing simulation model to accommodate fiber preform deformation during resin filling. This modified model was used to simulate the vacuum-bag RTM.

The vacuum-bag RTM is made possible by the presence of high-permeability layers. The effectiveness of high-permeability layers was therefore analyzed and compared with experiments. In addition, a rapid prototyping technique for RTM molds was studied using the laminated object manufacturing (LOM) process.

2. 3 Task 3: Intelligent Cure Control (ICC) System

Manufacturing of thick composite structures requires a careful thermal control because of the possibility of exothermic overheating. Since the control of surface temperature is not felt immediately by the interior, a feedforward control scheme using an on-line simulation and an expert system was developed.

3.0 RESULTS AND DISCUSSION

Results of the present research have been published in the open literature. Therefore, only summaries of those papers are provided below.

3. 1 Composites Consolidation

A set of unified governing equations have been derived to describe the consolidation process inherent in composites manufacturing. These equations can be applied to different processes with proper modifications. As a first step to verify their validity, these equations were applied to an autoclave molding process where resin flow is mostly through the thickness. The composite during cure was modeled as a deformable porous medium filled with liquid resin. A generalized Darcy's law and a fiber compaction model were used in combination with appropriate force equilibrium, mass balance and energy balance equations to simulate curing of a thick laminate. A finite difference algorithm was implemented to calculate the thickness change as a function of time. The predictions were compared with experimental data to elucidate the complexities of boundary conditions. The simulation model was also used to study the effect of aging on consolidation behavior [14, 18, 19, 22, 31].

Residual stresses induced during towpreg winding of a thick cylinder were predicted using an effective viscoelasticity model. Pressure was measured at the mandrel/composite interface during hoop winding to provide experimental correlation. The calibrated model showed that the fibers in the interior of the cylinder were in compression; however, the compressive stresses were rather small [1].

A process simulation model was developed for the thermoplastic tape placement process. The model included the entire process ranging from heat transfer to viscoelastic stress development to bonding development. The model was found to be in good agreement with a limited amount of data available in the literature [2, 3, 4, 11, 21]. This model was extended to simulate the laminated object manufacturing process, a rapid prototyping process similar to the tape placement process [6, 20].

3.2 Resin Transfer Molding

A finite-element-based algorithm has been developed to simulate resin transfer molding process. The algorithm is based on the concept of using partial saturation at the flow front to compensate for the discrete nature of conventional finite element formulation. In the new algorithm, convergence is guaranteed regardless of the size of the element or the time step used. Furthermore, it can accurately locate the flow front even if a coarse mesh is used. Being based on conventional finite element methods, it can be adapted into existing codes with little effort.

The resulting code RTMSIM can solve three-dimensional and non-isothermal problems. A special procedure for non-Newtonian fluids has also been implemented. The code has been validated by comparing its predictions with closed-form solutions for isothermal and non-isothermal resin transfer molding problems. RTMSIM is a robust program that can be used effectively with minimal user understanding of numerical methods. Furthermore, RTMSIM is equipped with an X-window based graphical user interface for flow visualization and has a postscript driver to generate hard copies of contour plots [8, 15, 23, 25, 26, 27].

In addition to the development of the aforementioned simulation code, experiments were carried out on vacuum-bag resin transfer molding and conventional resin transfer molding. The effectiveness of high permeability layers used in vacuum-bag RTM was analyzed and validated experimentally. The laminated object manufacturing process was used to fabricate molds to show how the product development cycle time could be reduced [7, 9, 12, 17, 24]. It was also demonstrated that an optical fiber could be used to monitor resin flow inside a mold [24].

The fiber compressibility inherent in VBRTM was included in an existing RTM code based on a finite-element/control volume approach. The unified consolidation model discussed earlier was used to account for the fiber preform swelling resulting from resin infusion [29]. The main mechanisms of void formation in RTM were found to be the result of non-uniform flow fronts at the fiber tow level [30].

Mechanical properties of VBRTM composites were investigated experimentally. It was found that RTM composites were comparable to those fabricated from prepregs [10, 13].

3.3 Intelligent Cure Control

An intelligent cure (IC) control system has been developed for compression molding by integrating an expert system shell with a process model. In the system, predictions from a process model are combined with a heuristic knowledge base on processing to make control decisions. The goal was to control the heat-up rate to maintain the through-the-thickness temperature distribution as uniform as possible in thick laminates. A one-dimensional heat transfer model coupled with a cure kinetic model and a viscosity model was used to determine the temperature distribution within the laminate. At each decision point, these simulation models were used to forecast the material state at a designated future time so that the system can respond in real-time to avoid any undesirable conditions in the future. By incorporating a forecasting ability, the IC system was able to minimize potential temperature overshoots inside the laminate [16].

The current IC system incorporates simulation models for Hercules AS4/3501-6 and AS4/3502 prepregs. The IC system requires accurate kinetic parameters to predict temperature distribution because simulation is sensitive to changes in those parameters. Thus a new cure kinetic model was developed for AS4/3502 to accommodate the dependency of the maximum degree of cure on temperature. The improved performance of the model was verified by providing an experimental correlation for the dynamic differential scanning calorimetry results predicted from the isothermal data [28].

The effect of process parameters on compression strength was investigated using a design of experiments approach. As expected, process conditions which yield complete cure were found to result in higher compressive strengths [5].

4.0 CONCLUSIONS

Composites consolidation in various manufacturing processes has been studied from a unified point of view to develop a simulation model. As a result a master formulation is now available and can be tailored to each manufacturing process. Process simulation codes have been developed for the resin transfer molding and autoclave/compression molding processes. The other key results are summarized below:

1. A finite element code RTMSIM has been developed to simulate RTM. The code can handle non-isothermal injection of reacting, non-Newtonian resins. It fully employs a finite element formulation without the use of control volumes, and therefore facilitates design and manufacturing integration.

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3. A rapid prototyping method based on the laminated object manufacturing process has been developed for RTM molds. The molds made of paper can be used for room-temperature RTM when their surfaces are treated properly.

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5. A unified process simulation model has been developed to bring analyses of different manufacturing processes under a general framework. The resulting master equation can be simplified depending on the pertinent process conditions.

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5.0 PUBLICATIONS

5.1 Journal Publications

1. E.A. Kempner and H.T. Hahn, "Effect of Radial Stress Relaxation on Fibre Stress in Filament Winding of Thick Composites," *Composites Manufacturing,* Vol. 6, 1995, pp. 67-77.

2. F. O. Sonmez, "Modeling of Heat Transfer and Crystallization for Thermoplastic Composite Tape Placement," *Journal of Thermoplastic Composite Materials*, Vol 10, 1997, pp. 198-240.

3. F.O. Sonmez and H.T. Hahn, "Thermoviscoelastic Analysis of the Thermoplastic Composite Tape Placement Process," *Journal of Thermoplastic Composite Materials*, Vol. 10, 1997, pp. 381-414.

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5. D.D. Shin and H.T. Hahn, "A Process Sensitivity Study of Composite Compressive Strength," *Journal of Thermoplastic Composite Materials*, Vol. 11, 1997, pp. 70-81.

6. F. Sonmez and H.T. Hahn, " Thermomechanical Analysis of the Laminated Object Manufacturing (LOM) Process," *Rapid Prototyping Journal,* 1998, Vol. 4, pp. 26-36.

7. M. Tari, A. Bals, J. Park, M.Y. Lin, and H.T. Hahn, "Rapid Prototyping of Composite Parts Using Resin Transfer Molding and Laminate Object Manufacturing," *Composites-Part A: Applied Science and Manufacturing*, Vol. 29, 1998, pp. 651-661.

8. M. Lin, H.T. Hahn and H. Huh, "A Finite element Method for Resin Transfer Molding Based on Partial Nodal Saturation," *Composites-Part A: Applied Science and Manufacturing*, Vol. 29A, 1998, pp. 541-550.

9. M. Tari, J.-P. Imbert, M.Y. Lin, A.S. Lavine, and H.T. Hahn, "Analysis of Resin Transfer Molding With High Permeability Layers," *ASME Journal of Manufacturing Sicence and Engineering*, Vol. 120, 1998, pp. 609-616.

10. J.-Y Wu, E. Kempner, M. Mitrovic, and H.T. Hahn, "Bearing Strength of E-glass/Vinyl Ester Composites Fabricated by VARTM," *Composites Science and Technology*, Vol. 58, 1998, pp. 1519-1529.

5.2 Conference Publications

11. F. O. Sonmez and H.T. Hahn, "Simulation of Crystallization Behavior During Thermoplastic Tape Placement Process," *Proc. 10th Int. Conf. on Composite Materials, Vol III: Processing and Manufacturing,* Woodhead Pub., 1995, pp. 325-332.

12. M.J. Tari, M.Y. Lin, and H.T. Hahn, "Resin Transfer Molding with High Permeability Layers," *Composites '97*, Society of Manufacturing Engineers, 1997, pp. 179-187.

13. T.J. Wu and H.T. Hahn, "Mechanical Properties of E-Glass/Vinyl Ester Composite Fabricated by VARTM," *Proc. 42nd SAMPE Int. Symp. & Exhibition*, Vol. 42, 1997, pp. 1-12.

14. E. Kempner, H.T. Hahn, H. Huh, "The Effect of Aged Materials on the Autoclave Cure of Thick Composites," *Proc. 11th Int. Conf. on Composite Materials* (CD-ROM), Vol IV, 1997, pp. 422-430.

15. M.Y. Lin and H.T. Hahn, "Lumped Mass Lagrangean Method for Heat and Species Tranport in Resin Transfer Molding," *Proc. American Society for Composites, 12th Tech. Conf.*, 1997, pp. 807-816.

16. D.D. Shin, L.L. Lai, and H.T. Hahn, "Thermal Control System for Thick Composite Laminates Based on Forecasting," *Proc. American Society for Composites, 12th Tech. Conf.*, 1997, pp. 882-891.

17. M.J. Tari and H.T. Hahn, "Rapid Process Development Techniques for Resin Transfer Molding," *Proc. American Society for Composites, 12th Tech. Conf.*, 1997, pp. 787-796.

18. E. Kempner and H.T. Hahn, "A Unified Approach to Manufacturing Simulation for Composites," *Proc. The First Korea-U.S. Workshop on Composite Materials*, Seoul, Korea, Sept. 1998, pp. 37-47.

19. D. Shin, E. Kempner and H.T. Hahn, "Compaction of Thick Composites: Theory and Experiment," to be presented at the 12^{th} International Conference on Composite Materials, Paris, July 1999.

20. S. Park, J.H. Park, M.K. Kang, and H.T. Hahn, "Optimization of Laminated Object Manufacturing Process Parameters for Composite Materials," *Proc. American Society for Composites, 13th Tech. Conf.*, 1998.

5.3 Theses

21. F. Sonmez, " Modeling of the Thermoplastic Composite Tape Placement Process," Ph.D. Thesis, UCLA, 1996.

22. E. Kempner, "Process Simulations for Manufacturing of Thick Composites," Ph.D. Thesis, UCLA, 1997.

23. M. Lin, "A Finite Element Simulation of Resin Transfer Molding," Ph.D. Thesis, UCLA, 1998.

24. M. Tari, "An Improved Resin Transfer Molding Process," Ph.D. Thesis, UCLA, 1998.

5.4 Submitted for Publication

25. M. Lin and H.T. Hahn, "A Finite Element Method for Non-Isothermal and Non-Newtonian RTM simulation," submitted to *Composites-Part A: Applied science and Manufacturing.*

26. M. Lin, M.K. Kang and H.T. Hahn, "Finite Element Analysis of Convection Problems in RTM Using Internal Nodes," submitted to *Composites-Part A: Applied Science and Manufacturing.*

27. M. Lin, M.J. Murphy, and H.T. Hahn, "Resin Transfer Molding Process Optimization," submitted to *Composites-Part A: Applied Science and Manufacturing.*

28. D. Shin and H.T. Hahn, "A Consistent Cure Kinetic Model for AS4/3502 Graphite/Epoxy," submitted to *Composites-Part A: Applied Science and Manufacturing* .

29. M.K. Kang and H.T. Hahn, "Analysis of Vacuum Bag Resin Transfer Molding Process," submitted to *Journal of Manufacturing Science and Engineering*.

30. M.K. Kang, W.I. Lee, and H.T. Hahn, "Formation of Microvoids During Resin Transfer Molding Process," submitted to *Composites Science and Technology.*

31. D. Shin, E. Kempner, and H.T. Hahn, "Compaction of thick Composites: Simulation and Experiment," to be presented at the 12th International Conference on Composite Materials, Paris, 1999.